Neutral Naturalness

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UCSB+Rutgers

Based primarily on work in progress with Simon Knapen & Pietro Longhi

LANL Santa Fe Summer Workshop 2014
"LHC after the Higgs" (Don't Panic)

TODAY'S TALK

MISSING TOP PARTNER PROBLEM

BUT, WHAT ABOUT THE TWIN HIGGS?

"THE ORBIFOLD HIGGS"

HIERARCHY PROBLEM!

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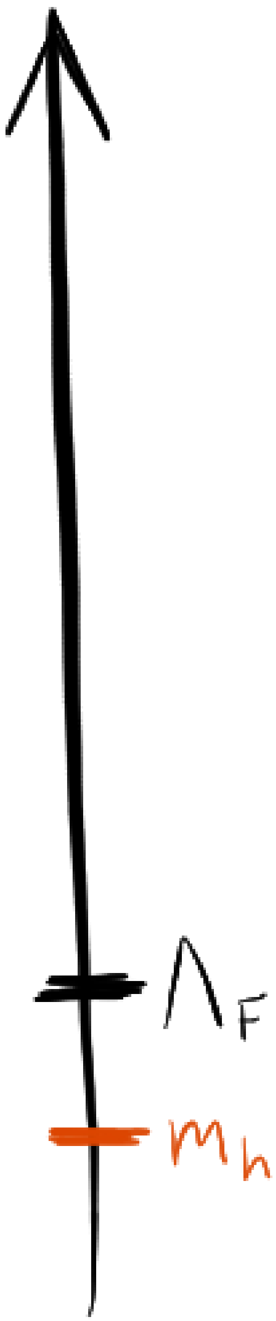
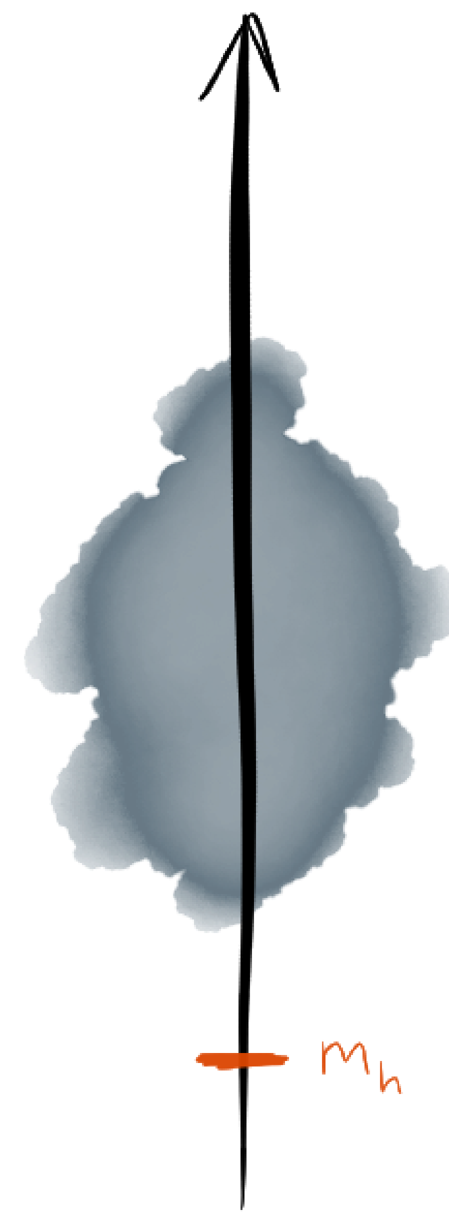


- ELEMENTARY SCALARS QUADRATICALLY SENSITIVE TO PHYSICS @ HIGHER SCALES.



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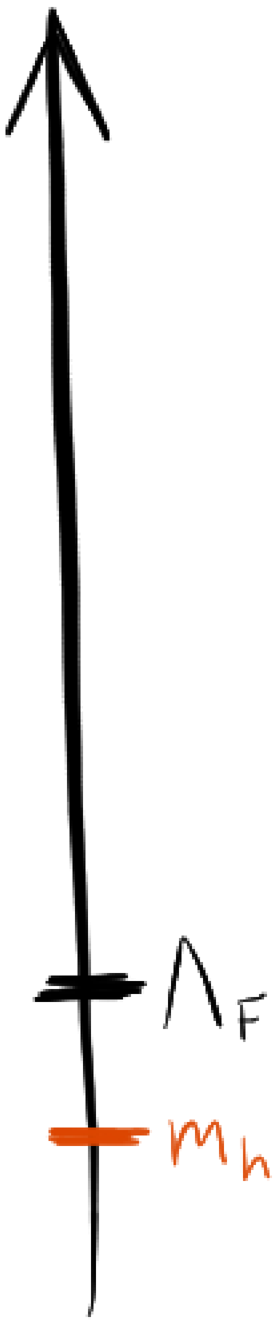

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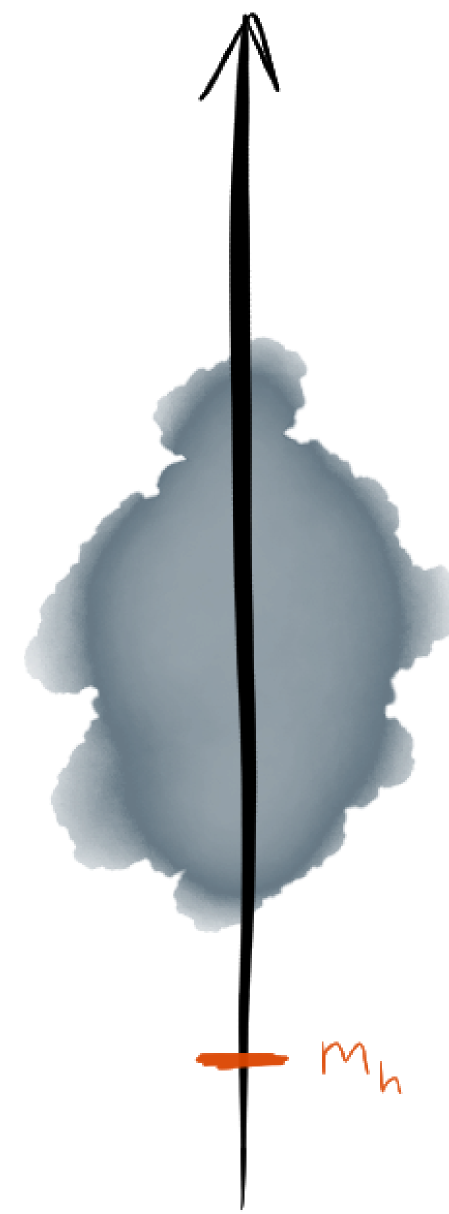

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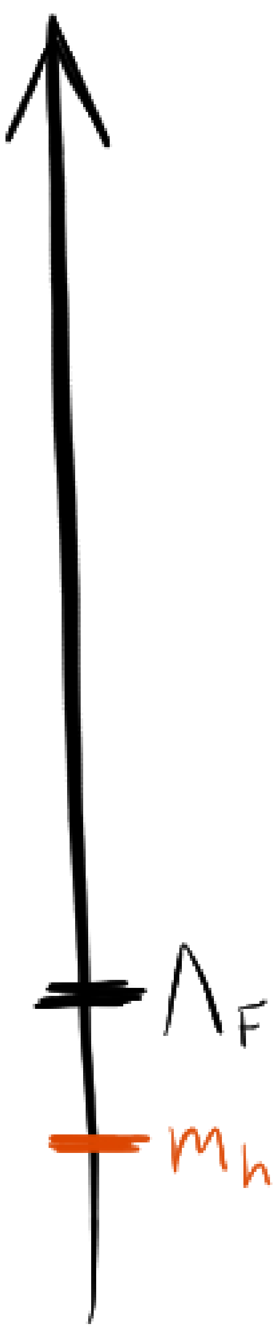

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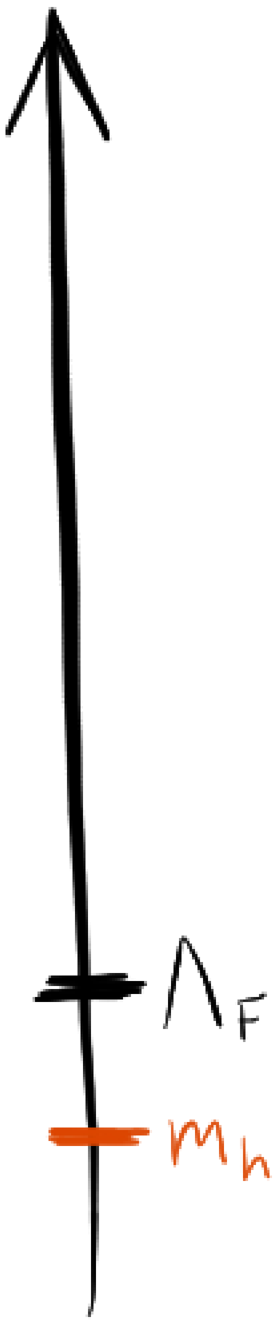

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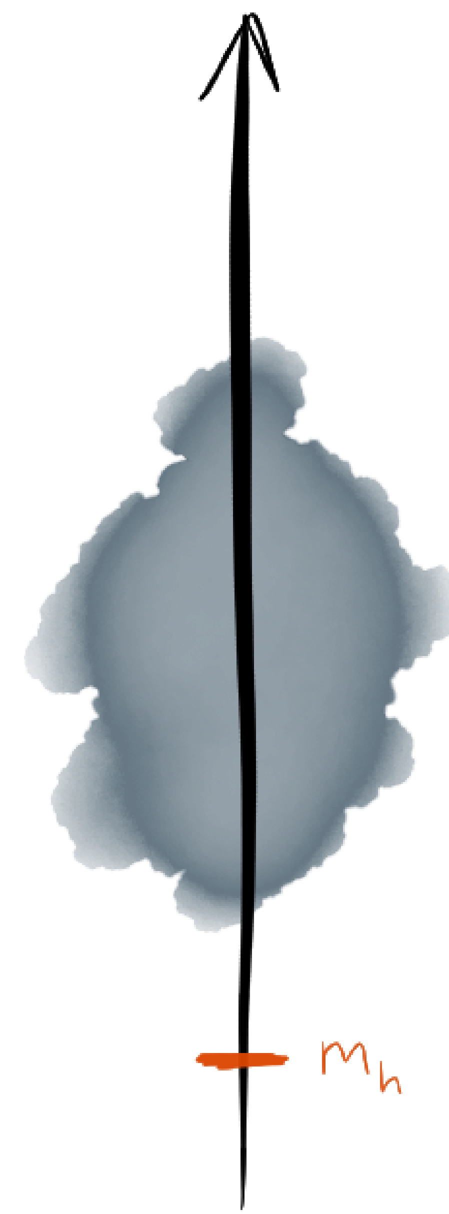
- PURE CUTOFF SOLUTIONS PUSHED TO ~5 TEV, DISFAVORED.



TOP PARTNER "THEOREM"

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TOP PARTNER "THEOREM"

- SYMMETRY PROTECTING HIGGS ACTS ON HIGGS ITSELF.
- LARGE HIGGS COUPLING: $\lambda_t H Q_3 t_R$, SO SYMMETRY ACTS ON TOP QUARK. IMPLIES TOP PARTNERS.
- TOP PARTNERS LIGHT, AVATARS OF SYMMETRY.

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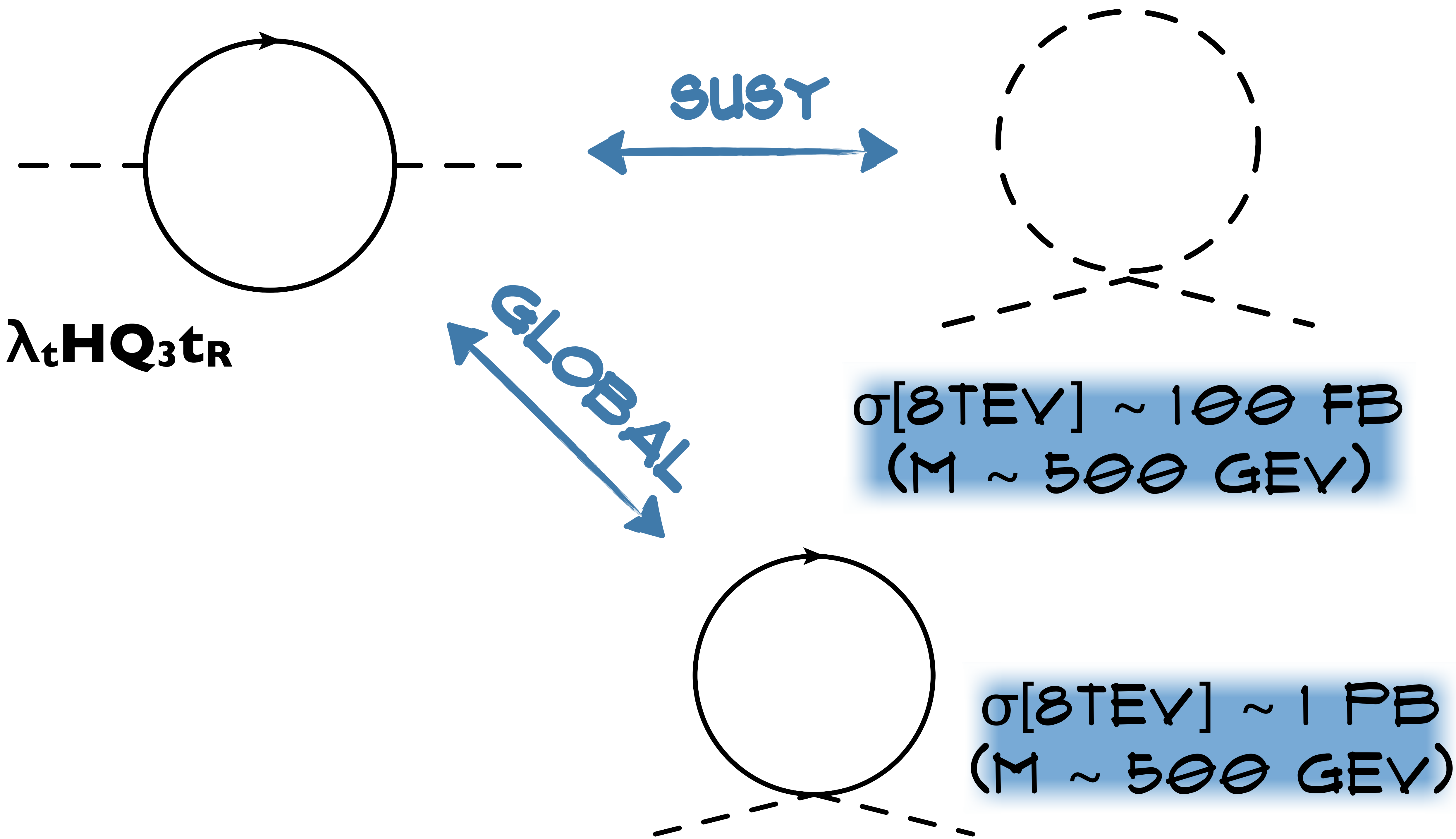
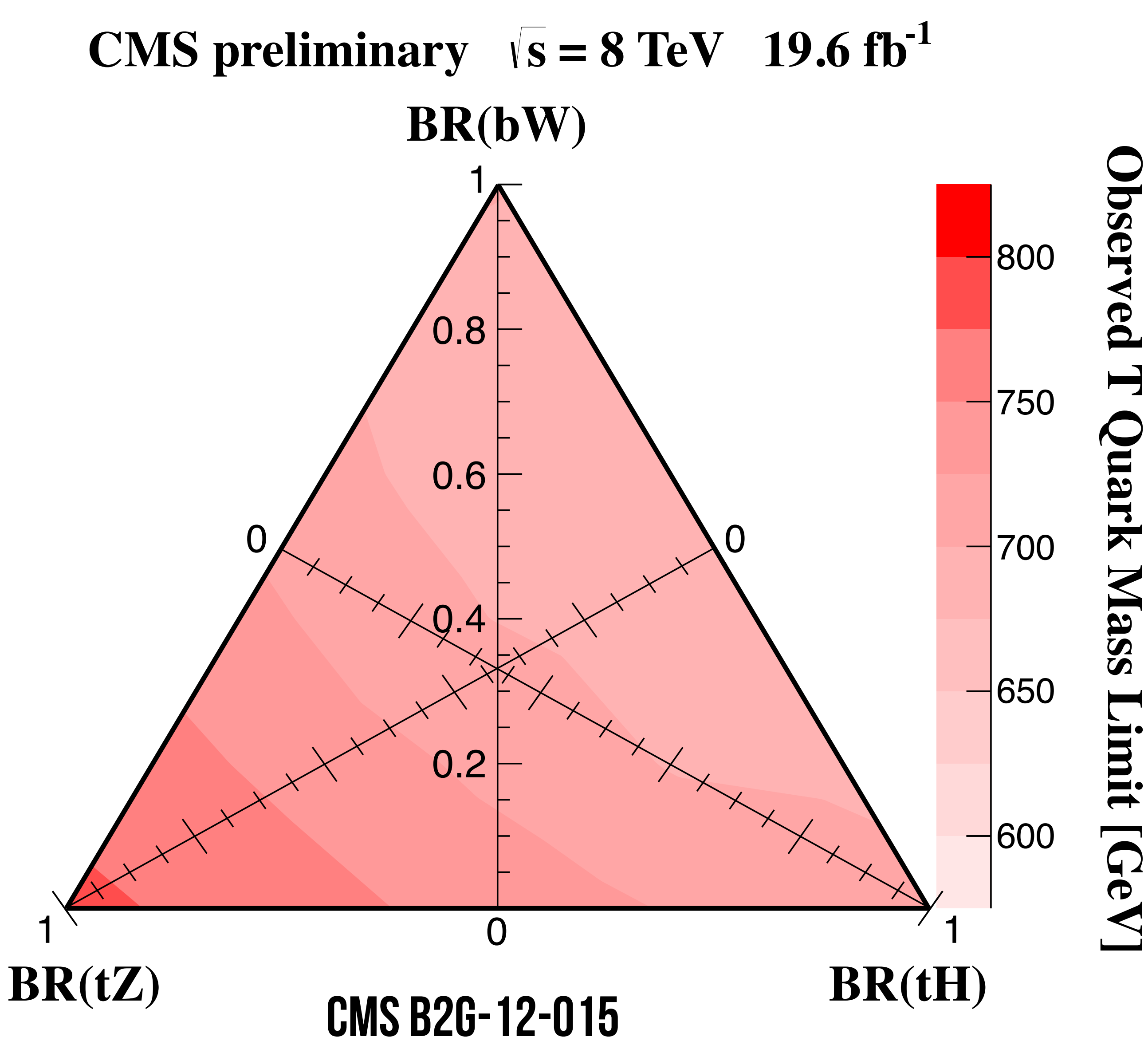
- SUSY: scalar top partners. Global symmetry: fermions.
- Decay modes vary but guaranteed large QCD cross section.

THE TOP PARTNER THEOREM

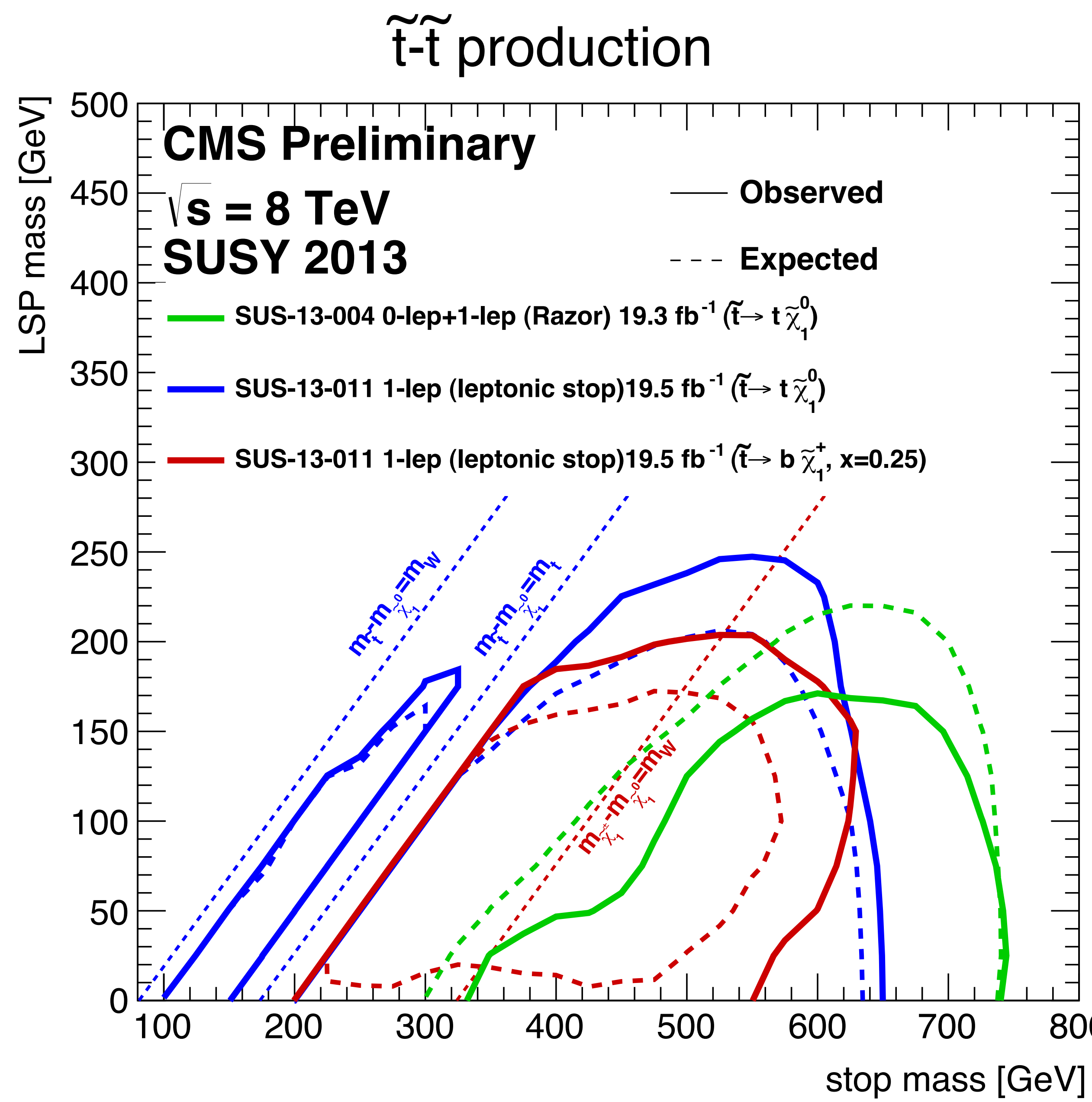


The Top Partner Problem

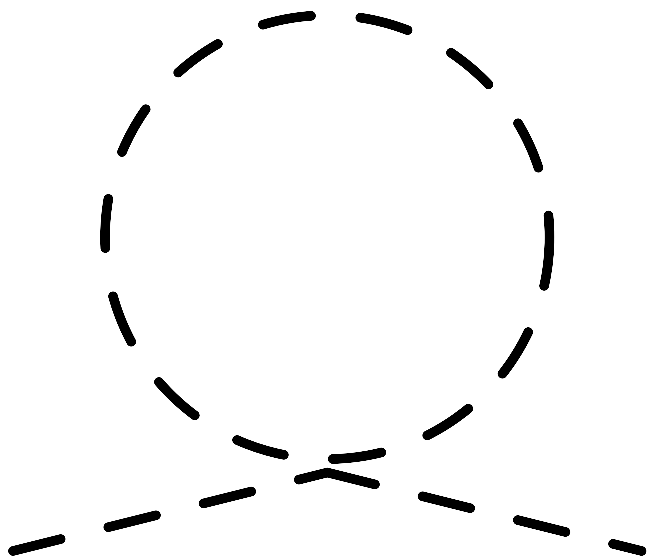
Global Symmetry



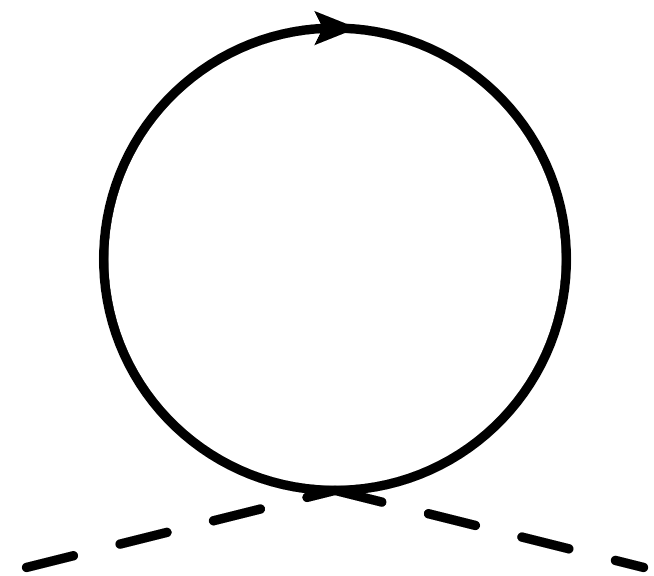
Supersymmetry



NATURALNESS?



$$\delta m_H^2 = -\frac{3}{8\pi^2}\lambda_t^2 \tilde{m}_t^2 \log(\Lambda^2/\tilde{m}_t^2)$$



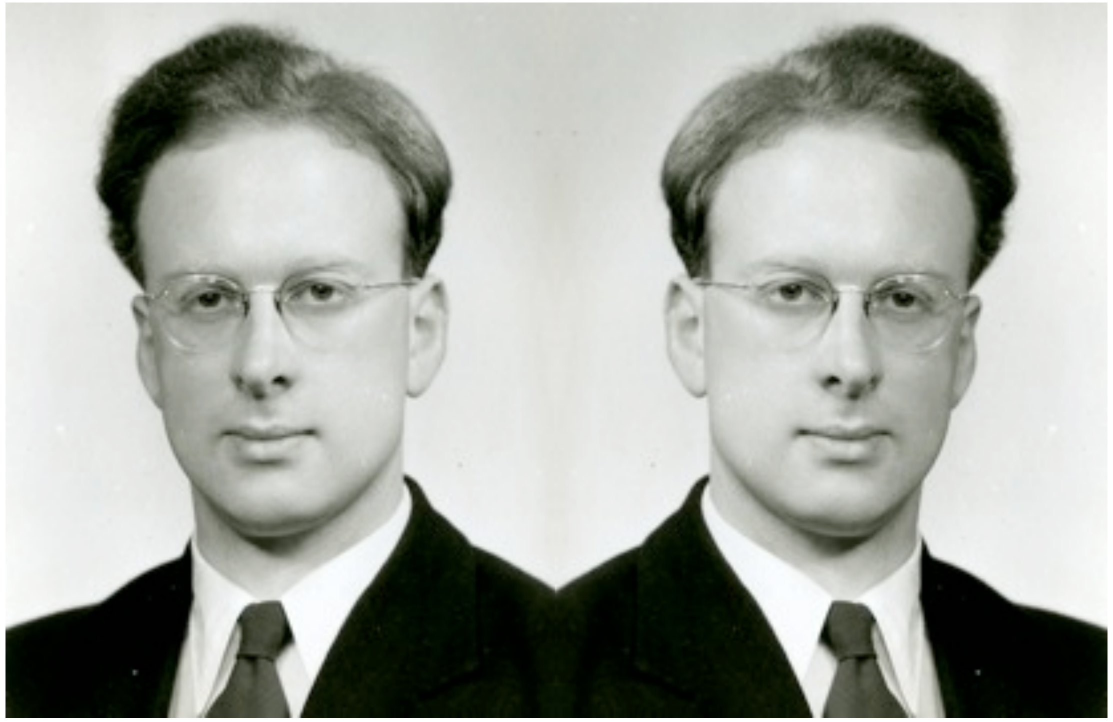
$$\delta m_H^2 = -\frac{3}{8\pi^2}\lambda_t^2 m_T^2 \log(\Lambda^2/m_T^2)$$

Irreducible tuning: ~5%. Complete model: $\lesssim$0.1-1%

BUT WHAT ABOUT...

THE TWIN HIGGS

[Z. CHACKO, H.-S. GOH, R. HARNIK '05]



electroweak constraints are satisfied by construction. These models demonstrate that, contrary to the conventional wisdom, stabilizing the weak scale does not require new light particles charged under the Standard Model gauge groups.

SYMMETRY IS $SM_A \times SM_B \times Z_2$

*SEE ALSO CHACKO'S TALK ON THURSDAY

THE TWIN HIGGS

CONSIDER A SCALAR H TRANSFORMING AS A FUNDAMENTAL UNDER A GLOBAL SU(4):

$$V(H) = -m^2|H|^2 + \lambda|H|^4$$

POTENTIAL LEADS TO SPONTANEOUS SYMMETRY BREAKING,

$$|\langle H\rangle|^2 = \frac{m^2}{2\lambda} \equiv f^2$$

$$SU(4) \to SU(3)$$

YIELDS SEVEN GOLDSTONE BOSONS.

UV: $\lambda \gg 1$ NLSM; $\lambda \lesssim 1$ LSM

THE TWIN HIGGS

NOW GAUGE $SU(2)_A \times SU(2)_B \subset SU(4)$, W/ $H = \begin{pmatrix} H_A \\ H_B \end{pmatrix}$

US

TWINS

Then 6 goldstones are eaten, leaving one behind.

EXPLICITLY BREAKS THE SU(4); EXPECT RADIATIVE CORRECTIONS.

$$V(H) \supset \frac{9}{64\pi^2}\left(g_A^2\Lambda^2|H_A|^2 + g_B^2\Lambda^2|H_B|^2\right)$$

BUT THESE BECOME SU(4) SYMMETRIC IF $G_A = G_B$ FROM A Z_2

Quadratic potential has accidental SU(4) symmetry.

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TWIN HIGGS SLOGAN

"HIGGS IS PSEUDO-GOLDSTONE OF THE ACCIDENTAL GLOBAL SYMMETRY OF QUADRATIC ACTION OBEYING DISCRETE SYMMETRY"*

*PLUS SYMMETRIC QUARTIC.

THE TWIN HIGGS

ACHIEVE THIS PROTECTION FOR THE ENTIRE SM BY $SM_A \times SM_B \times Z_2$

$\boxed{\textbf{SM}_A = \textbf{US, SM}_B = \textbf{TWIN SECTOR}}$

The Twin Higgs

Achieve this protection for the entire SM by $SM_A \times SM_B \times Z_2$

$\boxed{SM_A = \text{us}, \; SM_B = \text{twin sector}}$

Crucially: $\mathcal{L} \supset -y_t H_A Q_3^A \bar{u}_3^A - y_t H_B Q_3^B \bar{u}_3^B$

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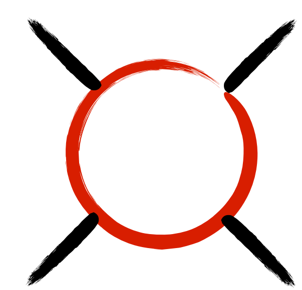
Explicit breaking generates one-loop quartic:



$$V \supset \kappa \left(|H_A|^4 + |H_B|^4\right) \qquad \kappa \sim \frac{y_t^4}{16\pi^2}\log(\Lambda/f)$$

(only quadratic potential enjoys SU(4))

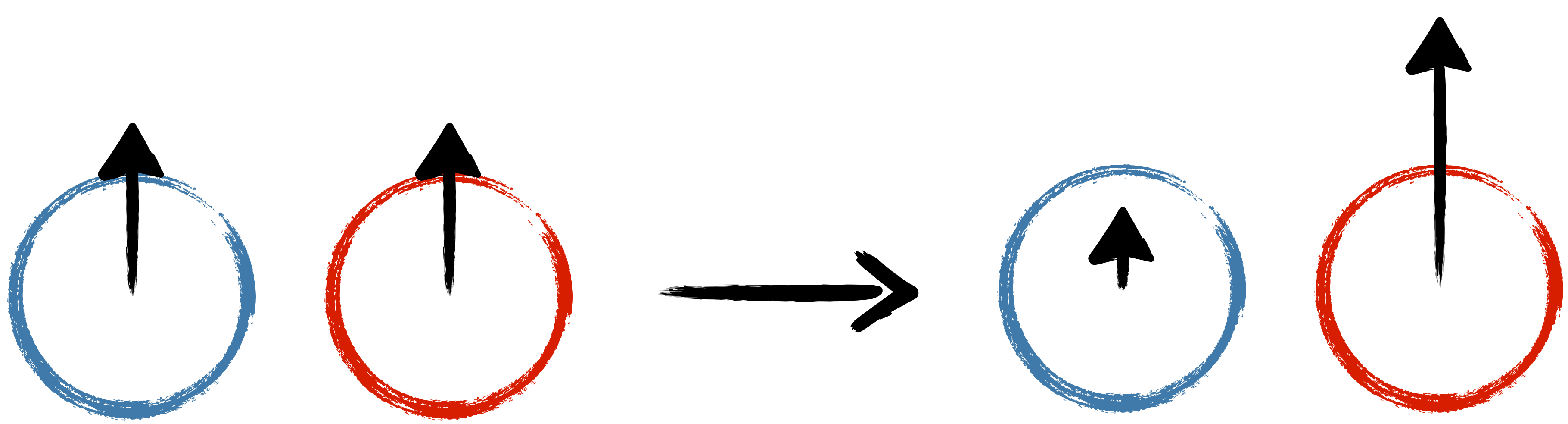
THE TWIN HIGGS

NAIVE VACUUM: $\langle H_A \rangle^2 = \langle H_B \rangle^2 = \dfrac{f^2}{2}$

F IS NOT FAR FROM V, AND THE CUTOFF IS ~TEV. NOT MUCH OF A PROTECTION, AND O(50%) DEVIATIONS IN HIGGS COUPLINGS.

OPTION 1: SOFTLY BREAK Z_2 $V_{soft}(H) = \delta m_H^2 |H_A|^2$

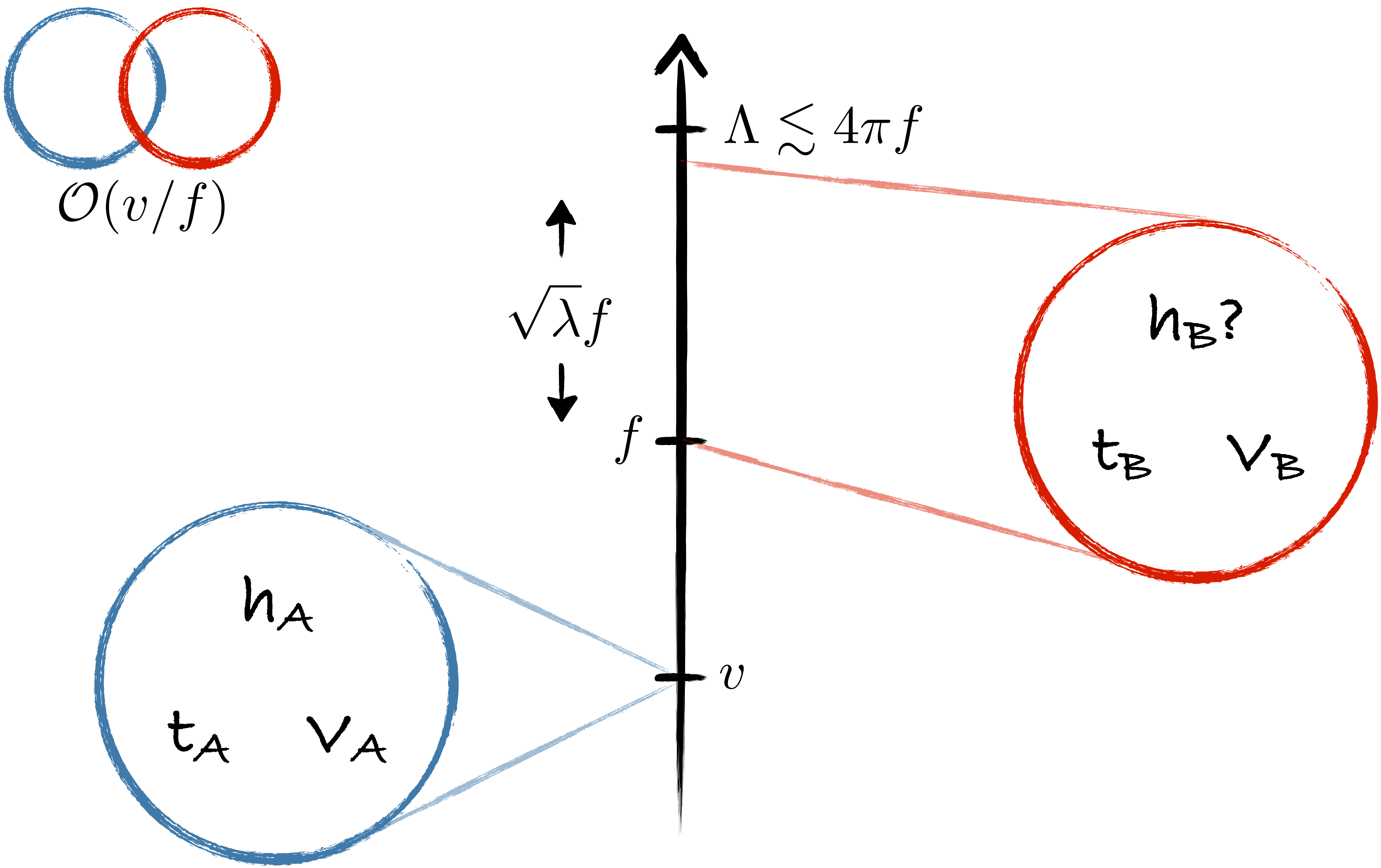
ALLOWS $v \ll f$, AT THE PRICE OF A TUNING $\sim\mathcal{O}(f^2/2v^2)$



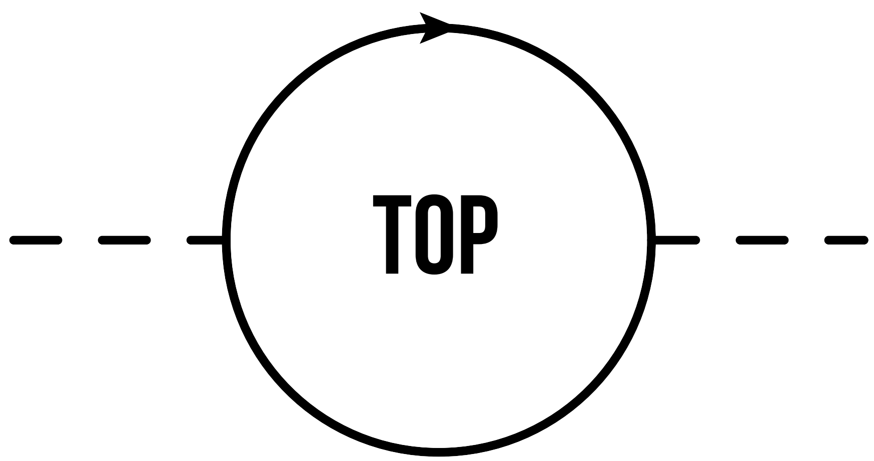
OPTION 2: HARD BREAKING OF Z_2

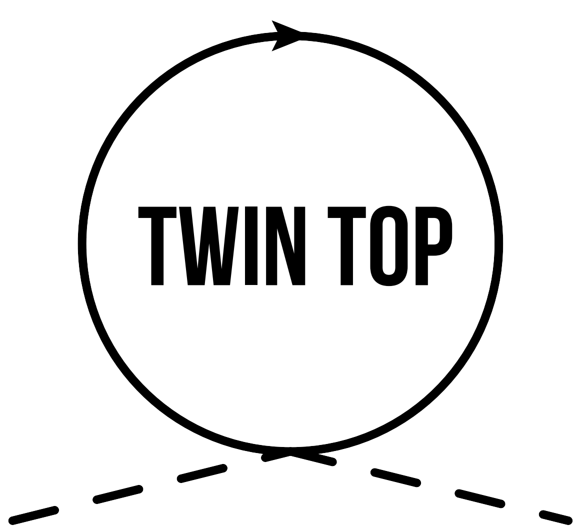
$$V_{hard}(H) = \delta_{A,B} |H_{A,B}|^4$$

THE TWIN HIGGS



THE TWIN TOP





THE TOP PARTNER ACTS AS EXPECTED FROM GLOBAL SYMMETRY PROTECTION, BUT NOT CHARGED UNDER QCD.

$$\mathcal{L} \supset -y_t H_A Q_3^A \bar{u}_3^A - y_t H_B Q_3^B \bar{u}_3^B$$

$$h + \ldots \qquad\qquad f - \frac{h^2}{2f} + \ldots$$

NO DIRECT LIMIT ON TOP PARTNER.

Where are the bodies buried?

Evades "top partner theorem", but...

- Demanding exact Z_2 means twin light generations; useless for naturalness but trouble for cosmology (N_{eff}).
- Symmetry structure slightly awkward; really asking for Z_2 *plus approximate SU(4) of Higgs potential.*

Bigger question: just a pathology, or example of deeper/general structure?

[Kachru & Silverstein '98; Bershadsky & Johansen '98, Schmaltz '99]

Orbifold Field Theory

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- Obtain a daughter symmetry by eliminating all fields not invariant under discrete symmetry (i.e. the untwisted sector of orbifold compactification).

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- E.g. parent SU(2N), discrete Z_2, daughter SU(N)xSU(N)xS_2, matter transforming only in irreps of the daughter.
- If the parent symmetry protects the Higgs, often the daughter does as well, but without the full representations required by the parent.

Sound familiar?

Twin Higgs is an orbifold

Parent: $SU(6)\times SU(4)/Z_2$

Various U(1) choices: $U(2)/Z_2$, $U(1)^2/Z_2$, $U(1)$; canonical choice $U(1)^2/Z_2$

Daughter: $[SU(3)\times SU(2)]^2\times S_2$

Canonical U(1) choice: $[SU(3)\times SU(2)\times U(1)]^2\times S_2$

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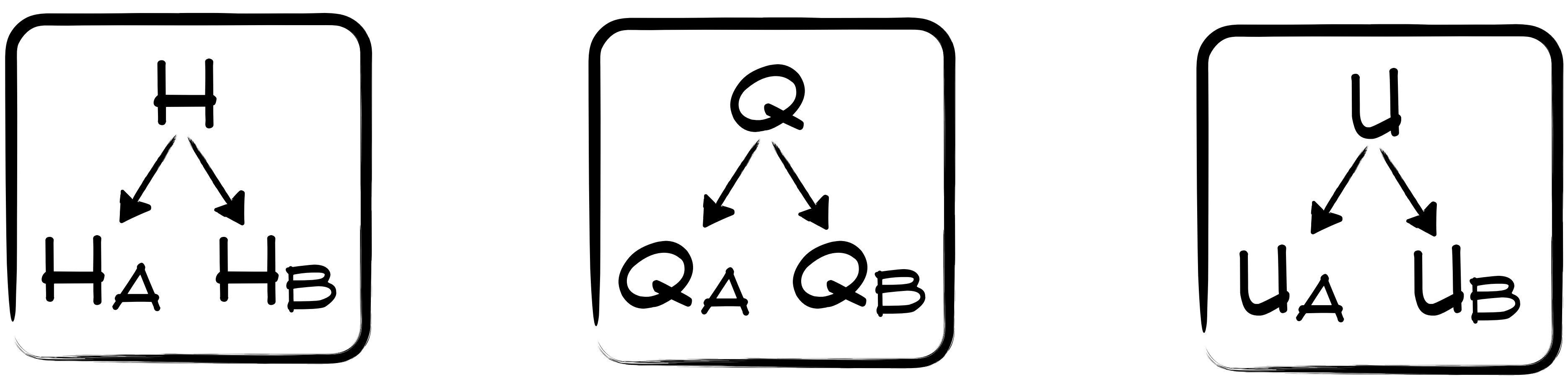

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$$\begin{tikzcd} & H \arrow[dl] \arrow[dr] & \\ H_A & & H_B \end{tikzcd} \qquad \begin{tikzcd} & Q \arrow[dl] \arrow[dr] & \\ Q_A & & Q_B \end{tikzcd} \qquad \begin{tikzcd} & U \arrow[dl] \arrow[dr] & \\ U_A & & U_B \end{tikzcd}$$

$$HQU \rightarrow \begin{cases} H_A Q_A U_A \\ H_B Q_B U_B \end{cases} \qquad |H|^4 \longrightarrow (|H_A|^2+|H_B|^2)^2$$

GIVES YOU ALL THE COUPLINGS REQUIRED BY TWIN HIGGS.

UV COMPLETIONS

WE KNOW HOW TO THINK OF ORBIFOLDS GEOMETRICALLY...

$SU(6)\times SU(4)$ $[SU(3)\times SU(2)]^2$

$H, Q_3, U_3\ (D_3?)$ $Q_{1,2}, U_{1,2}, D_{1,2}\ (D_3?)$

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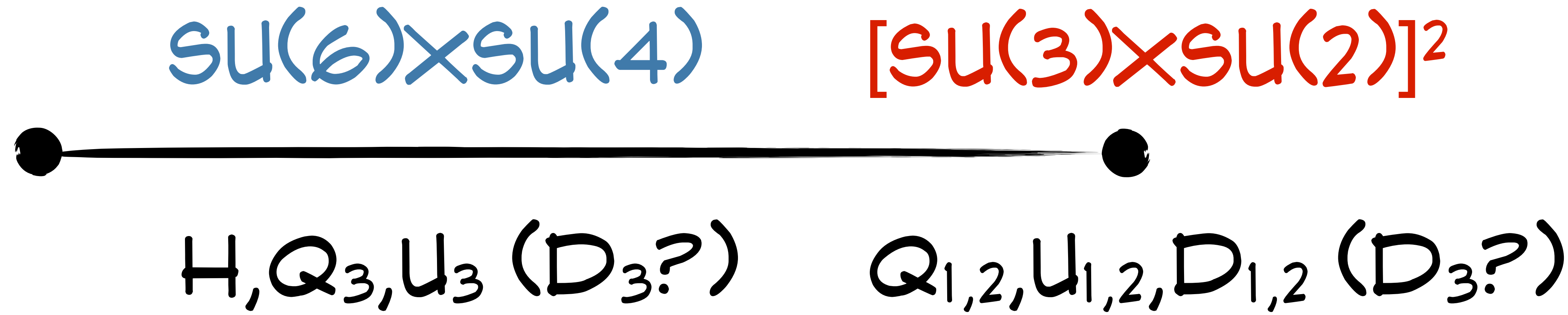
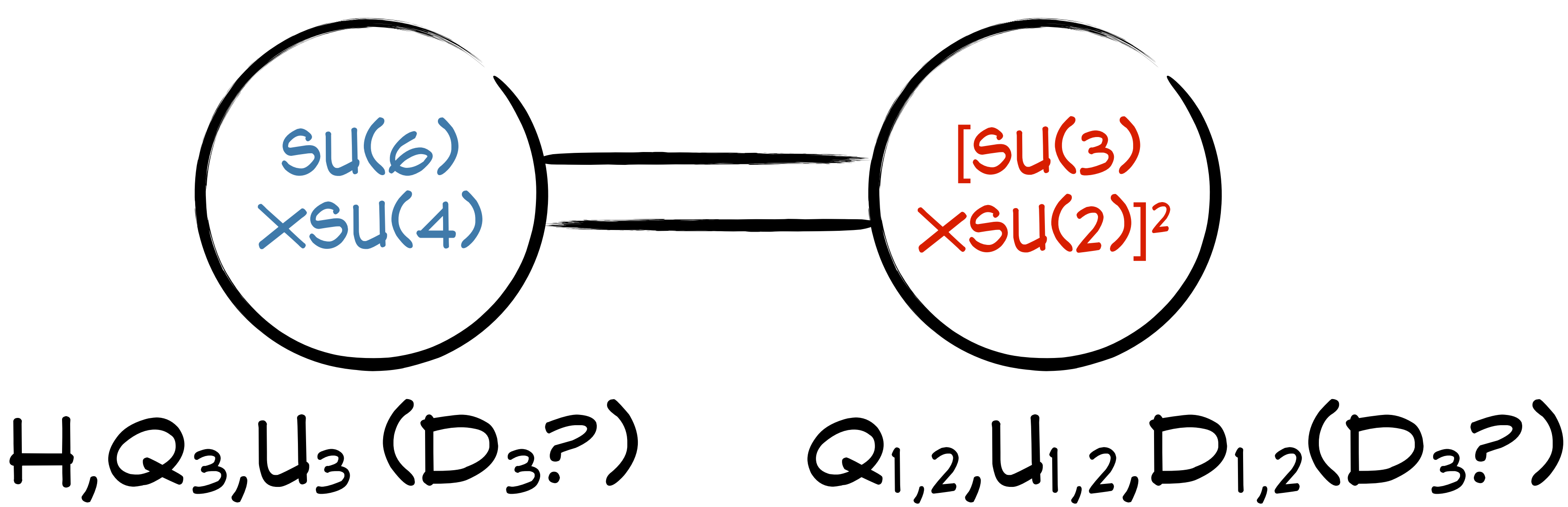


...OR BY DECONSTRUCTING THE GEOMETRY:



THE GENERALIZATION

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- SO WHAT ABOUT NON-ABELIAN DISCRETE SYMMETRIES? E.G. S_N, A_N, ETC. ***EXPECT SOMETHING QUALITATIVELY NEW.***

THE S_3 HIGGS

PARENT: $SU(18)\times SU(12)/S_3$

DAUGHTER: $[SU(3)\times SU(2)]^2\times[SU(6)\times SU(4)]$

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$L = HQU$

	SU(3)	SU(3)	SU(6)
u_A	$\bar{\square}$		
u_B		$\bar{\square}$	
u_C			$\bar{\square}$
u_D			$\bar{\square}$

	SU(2)	SU(2)	SU(4)
H_A	$\square$		
H_B		$\square$	
H_C			$\square$
H_D			$\square$

	3x2	3x2	6x4
Q_A	$\square\ \bar{\square}$		
Q_B		$\square\ \bar{\square}$	
Q_C			$\square\ \bar{\square}$

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$$L = HQU$$

	SU(3)	SU(3)	SU(6)
u_A	$\bar{\square}$		
u_B		$\bar{\square}$	
u_C			$\bar{\square}$
u_D			$\bar{\square}$

	SU(2)	SU(2)	SU(4)
H_A	$\square$		
H_B		$\square$	
H_C			$\square$
H_D			$\square$

	3x2	3x2	6x4
Q_A	$\square\ \bar{\square}$		
Q_B		$\square\ \bar{\square}$	
Q_C			$\square\ \bar{\square}$

"HIGGS IS PSEUDO-GOLDSTONE OF THE ORBIFOLDED SU(12) SYMMETRY"

HOW TO NORMALIZE YOUR ORBIFOLD HIGGS

NOT AT ALL OBVIOUS THAT RADIATIVE CORRECTIONS PRESERVE THE SU(12)! BUT ORBIFOLD CORRESPONDENCE DEMANDS IT...

How to normalize your orbifold Higgs

Not at all obvious that radiative corrections preserve the SU(12)! But orbifold correspondence demands it...

Given parent couplings g, Y, λ,

Field theory orbifold + canonical normalization of daughter states → d_α daughter sector inherits couplings

$$g \to \frac{g}{\sqrt{d_\alpha}} \qquad Y \to \frac{Y}{\sqrt{d_\alpha}} \qquad \lambda \to \lambda$$

Quadratic Sensitivity

CW potential for scalar transforming as a fundamental under SU($2d_\alpha$) with appropriate Yukawa:

$$\delta m_{H_\alpha}^2 = \frac{\Lambda^2}{16\pi^2}\left[-6 d_\alpha y_\alpha^2 + 3\left(d_\alpha - \frac{1}{4d_\alpha}\right) g_\alpha^2 + \ldots\right]$$

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$$\rightarrow \frac{\Lambda^2}{16\pi^2}\left[-6 Y^2 + 3\left(1 - \frac{1}{4d_\alpha^2}\right) g^2 + \dots\right]$$

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$$\rightarrow \frac{\Lambda^2}{16\pi^2}\left[-6Y^2 + 3\left(1 - \frac{1}{4d_\alpha^2}\right) g^2 + \ldots\right]$$

Total one-loop CW potential for S_3 Higgs scalars:

$$\propto \frac{\Lambda^2}{16\pi^2}\left[-6Y^2 + 3g^2 + \ldots\right]\left(|H_A|^2 + |H_B|^2 + |H_C|^2 + |H_D|^2\right)$$

SU(12) invariant ↗

~1/N orbifold corrections → $-\frac{3\Lambda^2}{256\pi^2} g^2 \left(|H_C|^2 + |H_D|^2\right)$

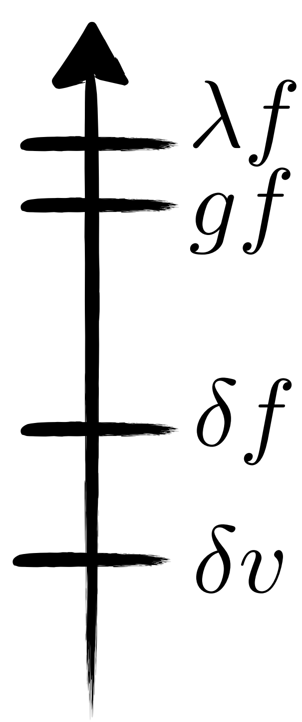
QUALITATIVE PHENOMENOLOGY

$SU(12) \to SU(11)$: 23 (PSEUDO)GOLDSTONES.
3+3+15=21 EATEN, 2 PSEUDOS REMAIN

Qualitative Phenomenology

SU(12)→SU(11): 23 (pseudo)Goldstones.
3+3+15=21 eaten, 2 pseudos remain

In typical vacuum $v \sim f$ & pseudos only partially aligned w/SM vev. As in twin Higgs, need to tilt potential to get $v \ll f$ & one SM-like pseudo.



- Radial mode, $m \sim \lambda f$
- Most Higgses eaten, $m \sim g f$
- One generic pseudo, $m \sim \delta f$
- One SM-like pseudo, $m \sim \delta v$

THE A_4 HIGGS

PARENT: $SU(36)\times SU(24)/A_4$

DAUGHTER: $[SU(3)\times SU(2)]^3\times[SU(9)\times SU(6)]$

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$3 \times$

$SU(3) \times SU(2)$

$H \quad Q \quad U$

$+$

$SU(9) \times SU(6)$

$H_1 \quad H_2 \quad U_1$

$H_3 \quad U_2 \quad U_3$

Q

THE A_4 HIGGS

PARENT: $SU(36) \times SU(24)/A_4$

DAUGHTER: $[SU(3) \times SU(2)]^3 \times [SU(9) \times SU(6)]$

$3\times$ [$SU(3) \times SU(2)$: H Q U] + [$SU(9) \times SU(6)$: H_1 H_2 H_3 U_1 U_2 U_3 Q]

$SU(24) \rightarrow SU(23)$: 47 (PSEUDO)GOLDSTONES.
$3+3+3+35=44$ EATEN, 3 PSEUDOS REMAIN

"HIGGS IS PSEUDO-GOLDSTONE OF THE ORBIFOLDED $SU(24)$ SYMMETRY"

REALISTIC MODELS

I'VE JUST SKETCHED TOY MODELS FOCUSING ON THE HIGGS POTENTIAL; FOR REALISTIC MODELS (E.G. HIGHER-DIM THEORIES), WE...

- NEED TO MAKE CHOICES FOR B_R; EITHER PART OF PARENT SYMMETRY (NEED 2HDM) OR NOT (LIVES AT DEFECT).
- NEED TO MAKE CHOICES FOR FIRST/SECOND GENERATIONS; SIMPLEST CHOICE IS TO LIVE AT DEFECT.
- NEED TO DEAL WITH ANOMALIES OF PARENT AND DAUGHTER SYMMETRIES.

NONE OF THESE ARE DEAL-BREAKERS, BUT IT HELPS TO DRESS THE FIELD THEORY ORBIFOLD.

THE TAKEHOME

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- Phenomenology of geometric twin Higgs can change radically!

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- EXPLAINS ALL THE PROPERTIES OF THE TWIN HIGGS, AND GEOMETRIC INTUITION FOR ORBIFOLDS POINTS TO SOLUTIONS TO CLASSIC PROBLEMS OF TWIN HIGGS.
- PHENOMENOLOGY OF GEOMETRIC TWIN HIGGS CAN CHANGE RADICALLY!
- THERE ARE ***MANY MORE THEORIES OF THIS TYPE***, WITH HIDDEN SECTORS NOT SIMPLY RELATED TO THE STANDARD MODEL!

The Big Picture

- Intense debate about naturalness post-Higgs, many conclusions being drawn.
- But we're far from writing down all natural theories using symmetries. Major loopholes in "top partner theorem."
- We should try reductions of all symmetry solutions to the hierarchy problem. Orbifolds of global symmetry only one avenue -- orbifolds also of R-symmetry? Orientifolds? Other stringy singularities?

Lots to explore before we pass judgment on naturalness!